NASA Facts

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Guidance and Control/ACEE

Figure 1: Lockheed's Advanced TriStar prototype, shown here in flight, was modified under NASA contract for research on active control systems and other concepts for energy-efficient aircraft design. Following the developmental phase of this work, Lockheed incorporated three concepts of the ACEE program—wingtip extensions, active controls and composite structure—into production transports in the L 1011-500 series.

Active control systems are under careful investigation by the National Aeronautics and Space Administration as one phase of the Aircraft Energy Efficiency (ACEE) program.

Application of active control systems to new or derivative transport aircraft holds the promise of more efficient overall aerodynamic design which, in turn, will help to achieve the aims of the ACEE program.

The basic goal is simply stated: Use fuel more efficiently.

ACEE is a ten-year planned program, developed in response to a request from the United States Senate Committee on Aeronautical and Space Sciences. It looks simultaneously at near-term and far-term problems, developing expedient solutions that can be applied to today's generation of aircraft, to their derivatives expected in a few years, and to wholly new classes of aircraft designed specifically to be fuel-efficient.

Several NASA research centers divide the workload of the ACEE program. Langley Research Center, Hampton, Virginia, is responsible for technology programs in both aerodynamics and in materials and structures. Wind-tunnel testing is shared by Langley and the Ames Research Center, Moffett Field, California. In-flight research is conducted by the Dryden Flight Research Center, Edwards, California. Propulsion research is at the traditonal site for such work, the Lewis Research Center, Cleveland, Ohio.

Overall, the broad aim of the ACEE program is to provide an inventory of technology that can be used by

Figure 2: This model of Lockheed's Advanced TriStar prototype is marked to show areas developed under the NASA ACEE program. Active controls, wingtip extensions for aerodynamic improvements, and the major composite structure, are shown. One goal of the NASA ACEE program was to develop improvements that could be applied relatively inexpensively and efficiently to existing aircraft or to their derivatives, as well as to completely new designs.

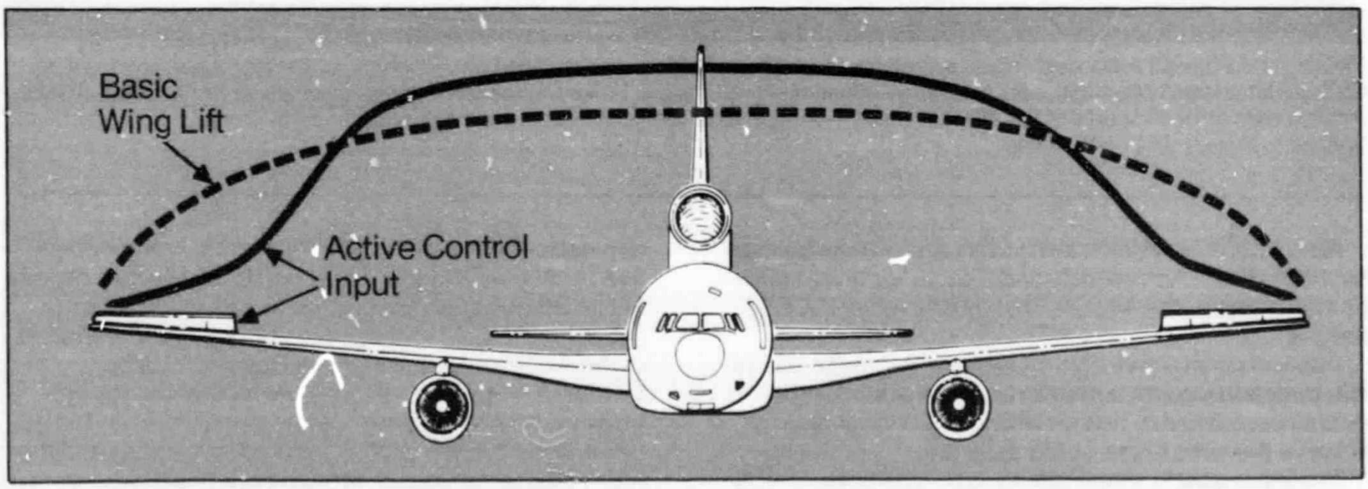

Figure 3: This sketch of a typical contemporary jet transport shows the theoretical lift distribution over the wing in level, unaccelerated flight (Dashed line in diagram). The use of active controls, which respond to the varying conditions of flight that produce accelerations and therefore change the airload distribution, changes the normal load distribution to a more favorable pattern (Solid line). The reduction of load at the wingtips and the shift of the major load to the wing roots means that the wingtip structure can be built more lightly to the required strength, and that the wing root accepts the extra load where it can be handled most efficiently.

the major air transport and engine manufacturers in the United States. It will help them develop near-term derivative airliners that extend their current product lines, to develop families of new designs for the near term, and perhaps to develop radically different aircraft for the far term.

One of the major portions of the ACEE program is the Energy Efficient Transport (EET). It concentrates on the development of advanced ideas that could produce a substantial, even a major, fuel saving. One aspect of the EET program is consideration of active control systems, the use of automated ways to deflect the control surfaces of an airplane to reduce undesirable motion or loading of the airplane.

There is a major difference in concept between active controls and the conventional use of aircraft surface controls. The latter are manipulated by command from the pilot, because he wants the airplane to move in a direction different from the one it has been flying. He wants it to turn, or climb, or descend. He applies the appropriate force to the cockpit control yoke, and the aerodynamic surface controls—rudder, elevators and ailerons—deflect and create forces that turn the airplane about its center of gravity in the desired direction.

Active controls operate independently of the pilot, in addition to whatever command he may be giving. Their motion is intended to generate forces to keep the airplane from doing something—from bounding around in turbulence, fluttering at high speed, straining the wing in a tight turn, or oscillating about a desired flight attitude.

Active control systems are intended to make things easier for the airframe, and in so doing, to make it possible to design and construct a lighter, more efficient airplane that will derive better performance from each gallon of fuel it consumes.

More Performance for Less Fuel

The concept of active control systems is not new; like some other aspects of the NASA Aircraft Energy Efficient program, it predates the oil crisis of 1974. In earlier concepts, active controls were seen as ways of reducing the physical size of the horizontal and vertical tail surfaces, thereby reducing drag and aircraft empty weight. Both of these improvements would contribute to improved performance and to operating economics.

It is still too soon to put accurate numbers on the gains in fuel economy to be realized by using active control systems. Further, active controls would be expected to be only one of several applications to reduce fuel consumption. The integration of active controls with other aerodynamic and propulsion improvements would produce a synergistic effect in which the fuel savings could total more than the sum of individual savings from each of the energy-efficient schemes.

One NASA estimate, though, sees fuel savings from five to ten percent as a result of the lighter weight possible through using active control systems. In contemporary and projected airline operations, a saving of even one percent of the fuel burned annually amounts to a tremendous amount of dollars, and is worth pursuing.

The reason is the cost of fuel. In the early 1960s, fuel costs were about one-fifth to one-quarter of the total direct operating costs (DOC) of the typical jet-powered air transport. Since then, a new generation of advanced powerplants has been developed and placed in service, and they have produced substantial reductions in specific fuel consumption: The actual pounds of fuel burned per pound of thrust generated per hour.

But that improvement in propulsive efficiency has been more than offset by dramatic increases in the price of fuel. Now, fuel cost is perhaps 60% of an aircraft's DOC, and this approximate tripling of the fuel cost factor is a major cause for concern.

How Active Controls Work

Active controls are automatic controls. Their function is simply stated: To improve airplane performance by stabilizing its flight, reducing departures from stable flight, and alleviating loads imposed by external factors such as gusts, turbulence, or maneuvers.

The two major concerned parties outside of NASA are the military, particularly the U.S. Air Force, and the commercial airlines. Both seek smoother rides for their aircraft and longer life for their airframes.

Much of the credit for early flight research work with active control systems goes to the Air Force, for a series of programs that stemmed from a major change in tactics. When the USAF decided that it has to make low-level approaches to targets to escape detection by enemy radar, it had to cope with a new set of problems imposed by flying fast at minimum altitudes. Low-level turbulence hammered the aircraft, disoriented the crew, and strained the airframe. Clearly something had to be done to alleviate the tremendous strain this imposed on the aircraft.

The commercial airlines don't enjoy flying through turbulence any more than the passengers do. But sometimes circumstances make it impossible to do otherwise. Traffic control, or the terminal environment on a bad-weather day, may require the commercial airliner to fly right through some of the worst turbulence around, simply because there is no airspace anywhere else to put that particular plane.

Some industry studies emphasized the advantages of active control systems. One major transport manufacturer found that the technology could be applied to produce an increase in the aspect ratio of the wing without an increase in weight. Since one component of cruise drag is the drag due to lift, and that in turn is a function of the wing aspect ratio, this offered an improvement in cruise performance that certainly could be translated into fuel savings.

Relaxed Stability Requirements

A concomitant of some active control systems is a relaxed static stability requirement. Aircraft normally are designed to be statically stable; they will return to

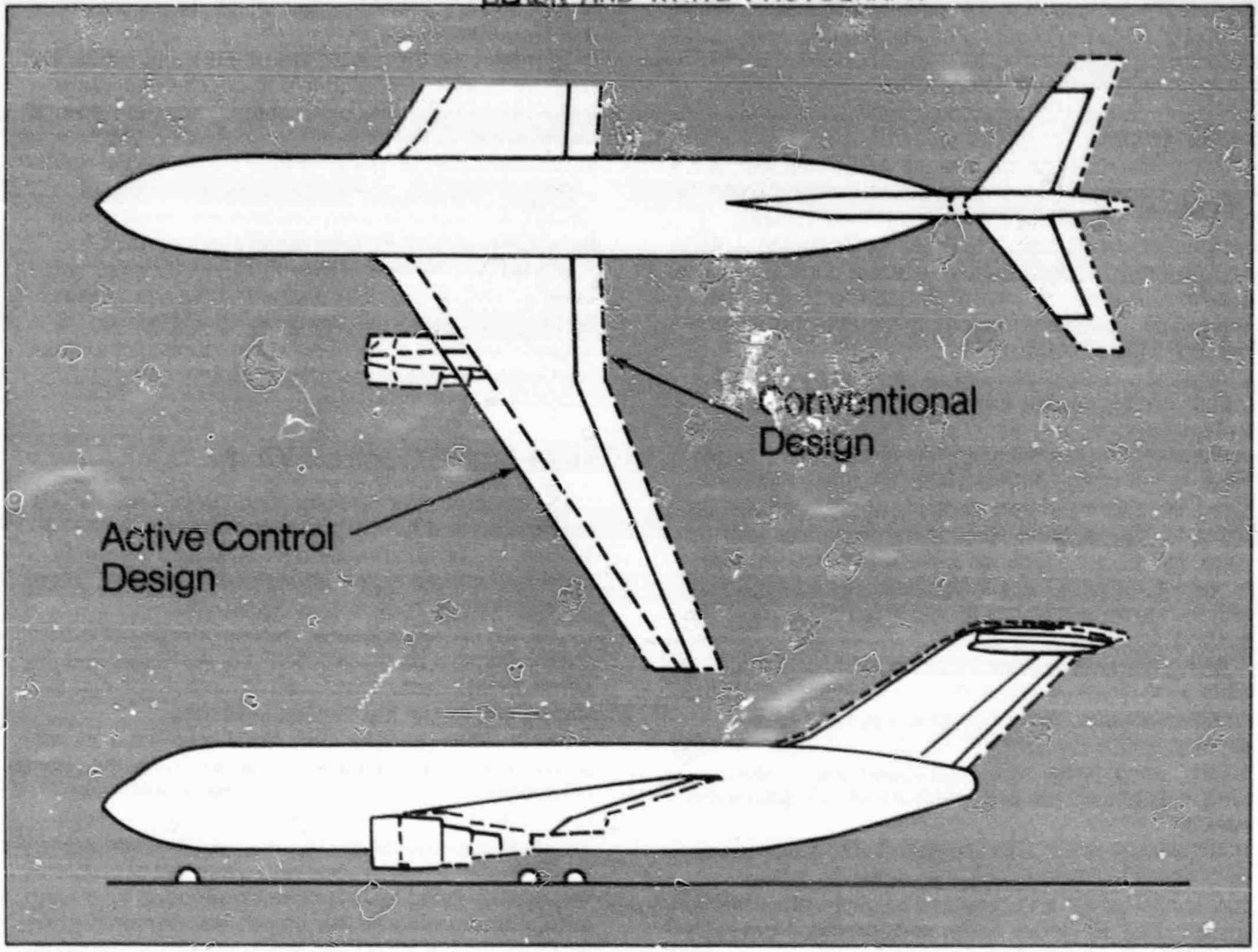

Figure 4: A comparison of contemporary transport configurations, one with and one without active control systems, points up the essential differences and the apparent advantages. The smaller horizontal tail and vertical tail surfaces mean that those structures can be lighter. That, in turn, moves the center of gravity forward, as indicated by the more-forward position of the wing in the active-control design layout.

their normal straight-and-level flight path when disturbed by a gust or a control input. They do this because of the stabilizing effect of their horizontal and vertical tails, and the dihedral of the wings. These surfaces provide forces that tend to maintain the airplane in stable flight. The aerodynamicist measures this stability in terms of a static margin: A percentage of the wing chord which represents the distance between the airplane's center of gravity and the wing's aerodynamic center, where its forces are assumed to be concentrated.

Relaxing the static stability requirements would be equivalent to moving the aerodynamic center nearer the center of gravity, nearer to the condition called neutral stability. Fighters tend to have a small, or zero, static margin; they have to be flown, hands-on, all the time, but they can easily be maneuvered.

Relaxing the static stability requirements, if done in a high-performance aircraft, would require that the airplane be flown all the time by some system that augmented the stability. That is what active control systems include among their several approaches to the problem.

Stability is not the only condition that is amenable to help from active control systems. Flutter, that bugaboo of aircraft designers, is another problem that may be eased, if not completely solved, by active control technology. Maneuvering loads, that superimpose bending stresses on the wing structure, can be redistributed through active control technology.

The ways and means for doing all of these things are under study in programs within NASA, and also in other programs that are being conducted by industry, both with and without NASA funding and contractual support.

Some Uses for Active Control Systems

Any aircraft responds to local turbulence in the air, riding the unsteady winds in an uneven pattern. Sometimes it seems to plow through, with the only evidence of turbulence being light, quick thumps that slightly jar

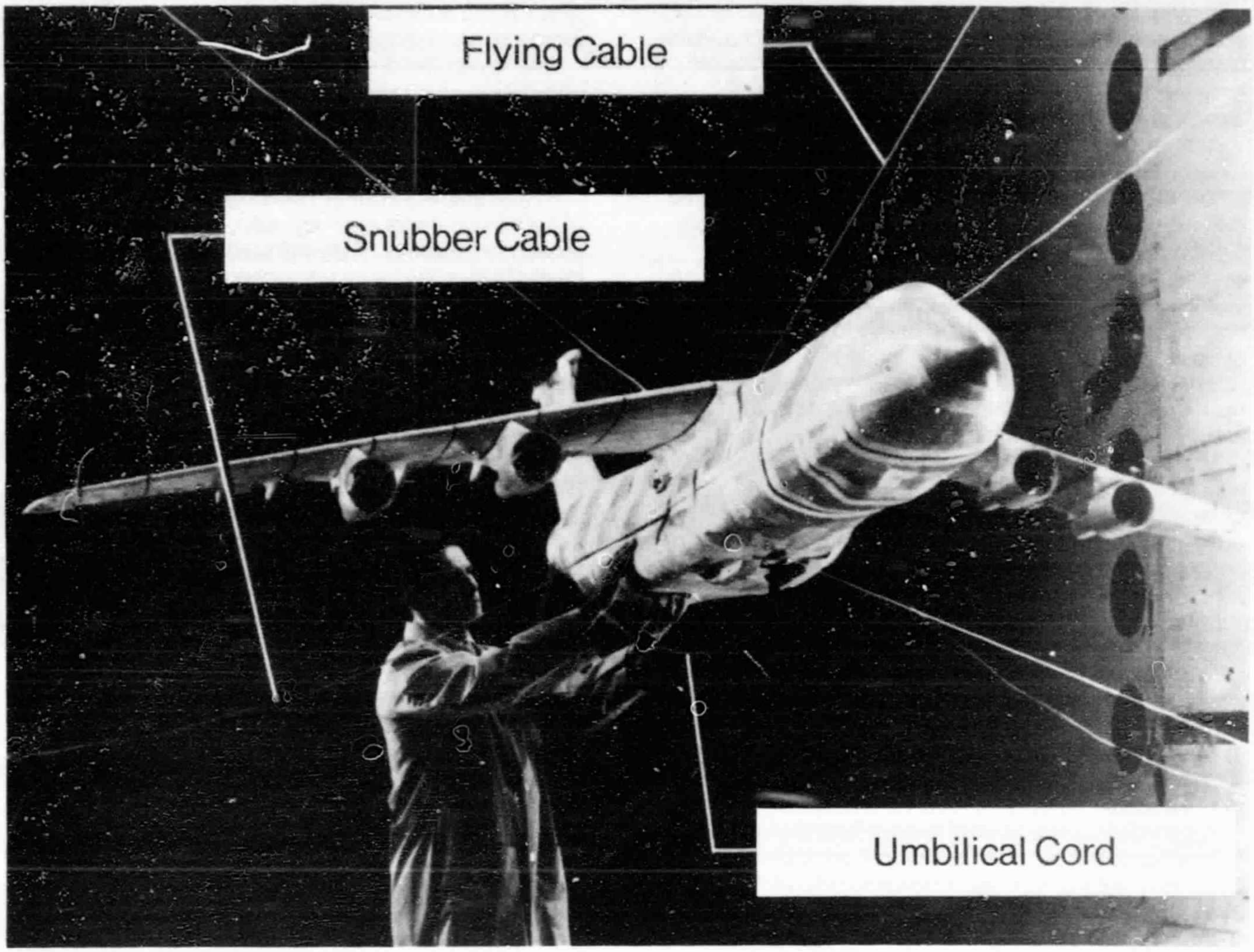

Figure 5: This dynamically similar model of the Air Force/Lockheed C-5A military transport was "flown" in a wind tunnel to assess the effects of active controls on its performance. The umbilical cord carried signals to the model's flight control system, as well as the instrumentation leads. The snubber cables to the model's left and right were for safety purposes, to keep the model from striking the test-section wall during its flight maneuvers. The flying cables supported the model. Tests like these provide an excellent means of making preliminary design studies, configuration changes, and evaluations of different concepts of control systems.

the airplane and its occupants. At other times it rolls, pitches and yaws, or does all at once in an amplified response to the atmospheric turbulence.

The pattern is completely random; there is no discernible design to its peaks and valleys that a pilot can anticipate and counter by moving the controls. But supppose that a sensor were mounted on a boom just ahead of the airplane's nose, and that it was connected through a complex analysis and control system to the rudder, elevators, and ailerons of the airplane. The boom-mounted sensor would feel the turbulence, the analyzer would determine its components and strength, and the control system would translate that data into a corrective control motion to moderate the effect of the turbulence. All this would take place in a tiny fraction of a second, far faster than any human could sense and react.

One such system exists and has been tested in flight on a USAF bomber. The type is referred to as a fatigue damage control system, because its primary function is to reduce the fatigue loads caused by turbulence. The continued imposition of unsteady loads, if allowed to continue long enough, can produce fatigue damage in aircraft structures, particularly wings. An active control system can help to reduce the imposed loads and therefore increase greatly the life of the aircraft.

Directly related to fatigue damage control systems, and stemming from the same tactical military problems, is the ride control system. Air Force bombers, flying fast and low, react to turbulence and produce bone-jarring vibrations in the cockpit. Crews simply cannot take the punishment; they are unable to focus their eyes on the instruments or on the outside terrain. A ride-control system was developed and tested to reduce that level of cockpit vibration. It used sensors to operate small control surfaces near the nose of the research aircraft, countering the input of turbulence and smoothing out the crew ride. Such a system is another form of active control technology under investigation by NASA, but the intended application may be quite different.

It might be useful, for example, to smooth the ride of short takeoff-and-landing (STOL) aircraft. They typically have low wing loadings and therefore tend to ride on turbulence much like a lightly loaded boat rides the waves, and with similar effect on passengers.

Active control systems also are used to augment the inherent stability of an aircraft, particularly when that inherent stability is low, or has been defined by relaxed requirements. Sensors detect deviations from a stable flight path, and transmit their readings to a stability augmentation system that controls rudder, elevator, and aileron motions. The artificial or augmented stability thus provided can meet all the needs for stable flight, even though it is not inherent in the airplane because of relaxed stability design criteria. Such active control systems have been developed, tested, and are in daily use.

Maneuvering imposes another set of loads on an aircraft. Instead of being the simple, symmetrical loads of level flight, they are unsymmetrical and multiplied, depending on the severity of the maneuver. Those off-center loads increase wing bending in a non-uniform way. That, in turn, influences wing weight, because wingbending is the important factor in designing the spanwise structure to accept that load as well as others. Reduced wing bending moments mean lighter wing structure and a more efficient aircraft. Consequently, NASA has been studying a maneuver load-control system that automatically deflects the wing trailing-edge flaps to change lift distribution and reduce wing bending moments.

Yet another active control system type tackles the difficult problem of flutter. An aircraft wing structure is, by its very nature, flexible. It bends to relieve its stresses. The bending is gentle, mostly unperceived except in the case of flight in severe turbulence. But the wing has a limit. If the airplane were flown fast enough, or maneuvered violently enough, the wing might respond by fluttering, vibrating in a pattern that could become so divergent and so severe as to tear the wing right off the fuselage.

Flutter traditionally has been controlled by distributed stiffness, to make the wing structurally resistant to the aerodynamic loads that trigger the flutter phenomenon. But an alternate approach is being studied by NASA. It uses sets of auxiliary aerodynamic control surfaces, moved automatically to increase the aerodynamic stiffness of the wing. That decreases the tendency toward flutter, and offers the possibility of reducing the structural stiffening required, which would reduce the structural weight of the airplane.

Redundancy and Reliability

In recent years, the realm of high-speed flight at high altitudes has made the achievement of simple aerodynamic stability very difficult to maintain over the entire flight envelope. Consequently, stability augmentation systems have taken over parts of the problem and currently are in common use on commercial transports.

The design of such systems calls for redundancy; if one set of stability augmentors should fail, there must be another one to take over. So multiple, redundant systems are the rule for safety. But that approach produces an obvious weight penalty for the airframe.

One reason for the use of redundant systems is the unreliability of contemporary components. They don't fail regularly, but they do fail, and redundant systems will guarantee safe operation in the event of failure of one or more components of a system.

Future stability augmentation systems, or other uses of active control technology, will use a different approach to reliability. They will seek the very highest level of reliability for all components in the system, rather than use multiple systems with lower levels of reliability.

These systems will be built, in all likelihood, around a central computer which will process the incoming data from sensors and translate that to commands to the various active control surfaces. Obviously, such a vital organ as the computer must be highly tolerant of faults in the system; if any occur, it must be able to detect them, analyze them, and compensate for them.

NASA is developing an advanced centralized computer system which continuously monitors all the flight control functions, the navigation, flight management systems, and all the displays, and evaluates them during flight. If a failure occurs in the system, the computer will identify the faulty processor or memory unit, and correct it by reassigning the task to another system or systems. It is possible, then, to lose a single unit of the system, but to receive its information content from other displays or processors, so that flight is in no way compromised through lack of pertinent information.

Digital Fly-by-Wire (DFBW)

Another way to lighten the redundant control systems is to replace the conventional hydraulic/mechanical type with an all-electrical and electronic type. NASA has done this in its Digital Fly-by-Wire investigation, a major program that will contribute its technology to the development of lighter and more efficient aircraft.

DBFW is not a formal part of the ACEE program; it is well along and in refinement rather than in development. Basically, it replaces hydraulics with electric and electronic components for a major saving in weight. DFBW was developed for NASA's Apollo program; similar analog systems had been used on the earlier Mercury and Gemini programs. The most-publicized contemporary application of DFBW is the installation in the General Dynamics lightweight fighter F-16A series, now in large-scale production in the United States and in Europe.

NASA modified the Apollo system for installation and tests on a Vought F-8 fighter aircraft, flown in an extensive program at the Dryden Center. It has completed more than two years of flight research experiments and ground tests, which have included such refinements as an investigation of simulated lightning strikes on the aircraft to check the effect on the all-electric system.

The technology of the NASA system has been applied to the design of the fly-by-wire control system of the General Dynamics F-16A lightweight fighter now in

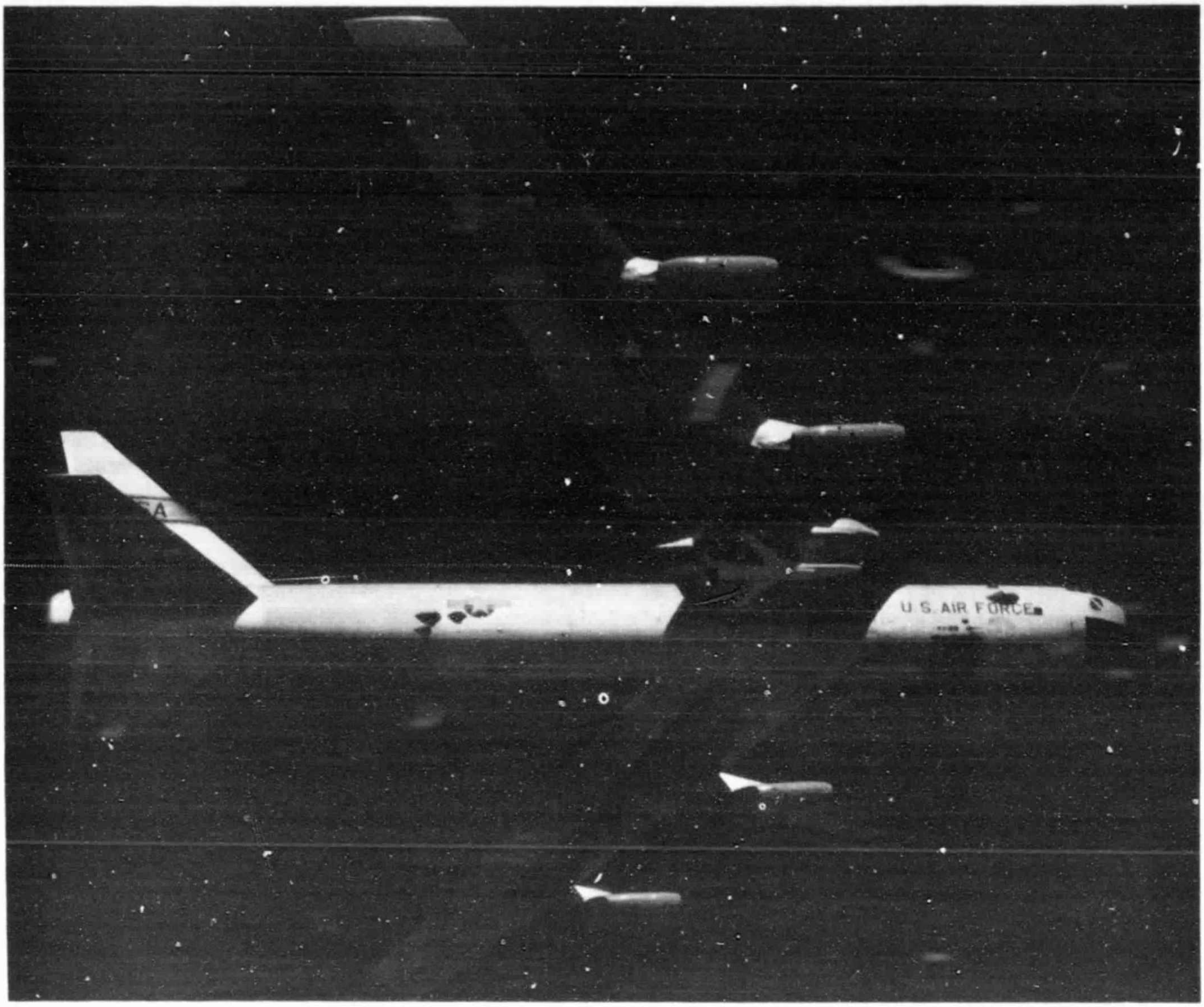

Figure 6: Snuggled underneath the starboard wing root of this NASA Boeing B-52D launch aircraft is a small, unmanned aircraft with a swept wing. This flight research vehicle is a modified Teledyne Ryan Firebee drone which has been fitted with a NASA test wing to evaluate active control systems. After launching from the B-52, the drone is flown by remote control by a pilot sitting at a control console on the ground. The DAST program—the acronym stands for Drones for Aerodynamic and Structural Testing—includes a series of tests to evaluate an active control system as a means of coping with wing flutter. The program is a joint one involving engineers and pilots from NASA's Langley and Dryden centers.

production for the USAF and for NATO countries. The F-16A system is quadruply redundant. Four sets of wiring harnesses transmit the motions of the pilot control inputs to drives located at the appropriate surfaces. The four harnesses are separated in their runs in wing and fuselage, so that battle damage will not knock out more than one at a time.

Technology and Trade-Offs

Paralleling this work on systems development are NASA assessments of the technology of sensors and actuators, to determine the current state of their art, and to develop means for improvement, if such improvement appears necessary or desirable.

Another important facet of NASA active control work in the ACEE program is a series of trade-off studies leading to a better definition of optimum flight control systems. A trade-off looks at all sides of the problem. It starts, generally, with the realization that a system can be improved. It needs updating here, a little more accuracy there, perhaps a lighter component or a better display there. But the newest gadgetry is more expensive; accuracy also costs money, as does lightness and the improved display. So the new and improved system will cost more. Can that cost be justified in terms of the performance improvement increment that it produces? Can a dollar value be placed on a better display or on a reduced pilot workload during flight in turbulence?

Those are the types of questions that form the base of trade-off studies.

Valuable input for such studies comes from the commercial airline operators, who have developed maintenance and realiability data, generally computerized, for their own operational guidance.

Such tradeoff studies can lead to "breadboard" hardware, in effect a complete advanced control system that is simply laid out on a series of panels without concern for developing a flightworthy system. That "breadboard" system then is thoroughly evaluated to determine its performance. The results become the foundation for the design of a flight system, to be evaluated again on the basis of safety and cost. The final step will be the detailed design of a flight-worthy active control system, complete development of the components and computer software, and a demonstration program to verify its performance and reliabilty.

Drone Flight Research

The flight research of active control systems could involve an element of risk as well as high cost. Taking a full-sized, manned aircraft out to its performance limits in order to define its flutter envelope accurately could put a very valuable research pilot at risk, as well as the aircraft. Further, the cost of even modifying, let alone building a new wing or a complete research aircraft is so high that some equally satisfactory, but less expensive alternate is almost mandatory.

Pilotless drone aircraft seemed to offer the answer; NASA now is using remotely piloted drones in a flight research program designated DAST (Drones for Aerodynamic and Structural Testing). The Teledyne Ryan BQM-34B "Firebee II" is launched from a modified Boeing B-52D mother ship, and is flown by a ground-based controller pilot who monitors the drone and flies it through a planned program of maneuvers.

Correlated with wind-tunnel testing, these experiments are evaluating active control systems as one phase of their planned flight research. Instrumented scale models of typical advanced wing designs are mounted on the drones for flight tests of active control systems. The drone technique also is used for other aerodynamic investigations.

The experimental technique first was validated by test flights of a standard wing that had been tested earlier in wind tunnels and in full-scale flight. The first tests of active controls were made on a small research wing with an aspect ratio of 6.8, designed for operation at Mach 0.92. Its active control system is used for flutter suppression; tiny, rapid-response control surfaces mounted at the wing trailing edge are actuated to create aerodynamic forces that dampen flutter by increasing the aerodynamic stiffness of the wing.

The second research wing for active control tests is typical of an energy-efficient transport, with an aspect ratio of 10.3. It incorporates active controls to alter the distribution of wing loads, and to moderate them to improve both wing structure life and flight safety.

The flight research on these models in the DAST program is expected to yield the first realistic evaluations of wings designed from the start around the concept of an active control system.

Full-Scale Flight Research

Budgetary and policy considerations limit the types and numbers of research aircraft that NASA can have under development or in operation at any one time. For that reason, important portions of NASA research programs in flight are accomplished by contractors in funded studies, using their own aircraft. A typical example is a flight evaluation of several active control concepts being performed by the Lockheed Corporation under contract to NASA.

The research aircraft is the company-owned prototype Lockheed L-1011 wide-bodied transport. The active control system, developed in-house by Lockheed with company funds, uses maneuver load control. Automated flap deflections redistribute the lift during turning flight. It also has a gust alleviation system, using sensors for detection and a computer to command control motions to reduce the effects of gusts on the flight. The complete system was designed specifically for the L-1011; it was tested extensively in simulator studies on an "iron bird", a non-flying representation of the aircraft with production flight control systems in full-sized installations.

After initial flight research for NASA, the L-1011 was again modified by adding wingtip extensions to investigate one way of reducing the component of drag due to lift. Further flight evaluation followed.

Although the L-1011 was not designed with relaxed stability requirements, it will serve as a test vehicle for an investigation aimed at the applicability of relaxed stability standards to a typical contemporary transport aircraft. That investigation will be conducted by analysis and simulation, and finally verified in flight.

Together, these studies, test programs and experiments in small-scale and full-scale flight are producing a body of advanced technology with a potential for application to the design of energy-efficient aircraft. Not all of it may be used; but all of it will be useful, in defining the problems, in offering solutions, and in contributing to the advancement of powered flight in an age of fuel crisis and conservation.

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